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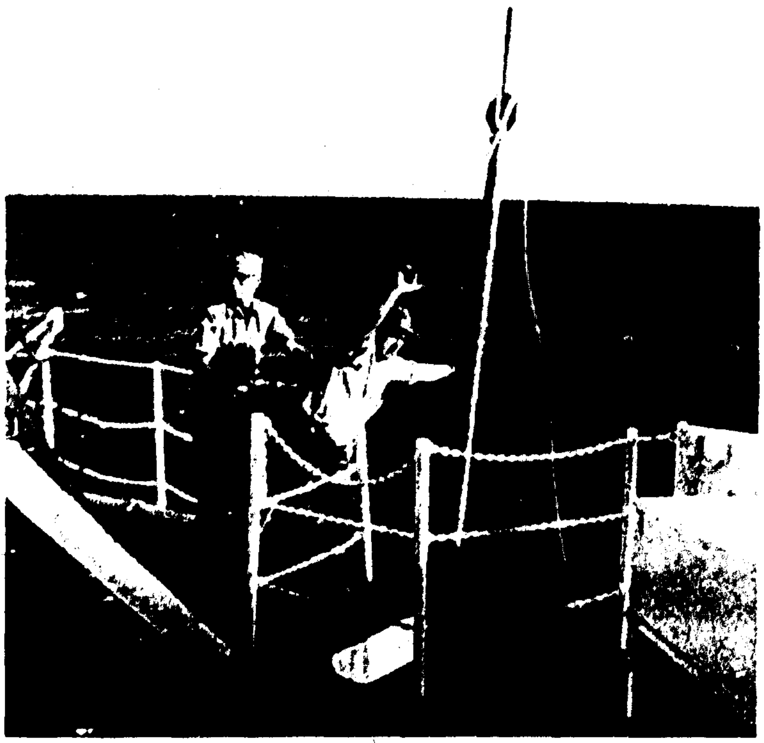

EXPENDABLE DOPPLER PENETROMETER: A PERFORMANCE EVALUATION

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An expendable penetrometer using the Doppler principle has been developed to expediently test seafloor soils to a depth of 9m (30 ft) at water depths to 6,000m (20,000 ft). The velocity of the penetrometer is measured as it penetrates seafloor soils. From the velocity record, soil penetrability and an estimate of the undrained shear strength profile can be calculated. The penetrometer has a mass of 173 kg (12 slugs), is 2.9m (9.5 ft) long, is 90mm (3.5 in.) in diameter, and is easily deployed from a ship. This (cont on p iv)

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An expendable penetrometer using the Doppler principle has been developed to expediently test seafloor soils to a depth of 9m (30 ft) at water depths to 6,000m (20,000 ft). The velocity of the penetrometer is measured as it penetrates seafloor soils. From the velocity record, soil penetrability and an estimate of the undrained shear strength profile can be calculated. The penetrometer has a mass of 173 kg (12 slugs), is 2.9m (9.5 ft) long, is 90mm (3.5 in.) in diameter, and is easily deployed from a ship. This report presents data from 11 tests at four locations off the southern California coast. Undrained shear strength profiles determined from penetrometer data are compared to other types of in-situ data and core data. It is concluded that the expendable Doppler penetrometer is reliable and simple to use and that reasonable estimates (±30% of actual values) of undrained shear strength profiles can be obtained even though the analyzed phenomenon is complex. This tool will be of particular value in surveying potential embedment anchor or foundation locations and can, for some cases, provide information sufficient for design purposes.

CONTENTS

INTRODUCTION

This report describes an expendable dynamic penetrometer and its associated ship-board electronics. An evaluation of the system's ability to determine seafloor penetrability and undrained shear strength is presented. Seafloor shear strength information derived from penetrometer data is compared to the best in-situ or laboratory shear strength data available. The overall objective in developing the dynamic penetrometer was to provide an expedient means for determining seafloor characteristics and properties relevant to site selection for design of direct embedment anchors.

Background

Installing embedment anchors requires knowledge about seafloor sediment strength, penetrability, thickness, and the occurrence of anamolous conditions (e.g., detritus and small submarine lava flows). These data must cover sediment depths to 9m (30 ft) plus at-water depths to 6000m (20,000 ft). The more data available on these factors, the more likely a successful installation will be made. The mainstays of site surveys to provide the required information are soil coring and acoustic profiling. Both are necessary. However, coring is time consuming, limited to fair weather, and, therefore, costly. Acoustic profiling tends to average the characteristics of large seafloor areas and does not measure engineering properties. To increase the flexibility and success of conducting seafloor surveys with these apparatuses a tool was needed that would decrease coring requirements and allow for better interpretation of acoustic profiling records. An expendable penetrometer could fulfill these requirements.

Penetrometers are expedient, usable in rough weather, and indirectly measure what is probably the most significant engineering property for designing embedment anchors—undrained shear strength. This property is also used when analyzing bearing capacity, breakout, and penetration problems. Penetrometers can be used to estimate this key parameter in conjunction with widely spaced cores, or independently when coring is not feasible because of weather or sea conditions. Penetrometers can also help interpret acoustic profile records where core data are either not available or remote by providing a link to undrained shear strength.

In the application of penetrometers to the design of direct embedment anchors, several factors must be recognized. First, a penetrometer will provide data (undrained shear strength) that are suitable only for estimating short-term holding capacity in cohesive soils. Fortunately, most deep ocean soils are near normally consolidated cohesive deposits in which the short-term holding capacity will govern the design because it is less than the long-term holding capacity. Second, the estimates of short-term capacity will only be as good as the undrained shear strength obtained. Penetrometers are not a way of obtaining ideal shear strength data, but they can provide data accurate enough for selecting fluke size and for making tolerable estimates of penetration and short-term holding capacity.

Sandia Laboratories began development of a seafloor penetrometer in 1970 (Colp et al., 1975), and Scott (1970) reported on a mechanical accelerometer for use with an ocean penetrometer. Delco Electronics developed an expendable soil bearing meter for use in the ocean that was similar to an expendable bathythermograph (Robertson, 1965). None of these devices was found suitable for the requirements outlined above. Their sizes are too small to obtain the required 9m (30 ft) of penetration, and they are not operable to a water depth of 6,000m (20,000 ft). Therefore, a new approach was necessary to obtain the performance required.

Approach and Scope

An expendable penetrometer utilizing the Doppler principle of a sound source moving in relation to the

receiver of the sound emitted was developed to provide the desired penetrometer capability (Thompson, 1977). In addition, a ship-board receiver and hydrophone were developed to monitor the Doppler data from the penetrometer and provide an analog of the velocity of the penetrometer as it embeds into the seafloor. With these data can be recovered at water depths to 6,000m (20,000 ft) with 9m (30 ft) of sediment penetration.

To verify the feasibility of a Doppler penetrometer and to show that satisfactory data can be obtained with it, tests were conducted at four sites off the southern California coast. The reduced data were then compared to the best in-situ or core data available. A performance evaluation of the penetrometer system based on the at-sea work and the data comparisons is presented.

DESCRIPTION OF TEST APPARATUS

The expendable Doppler penetrometer system has the following components: (1) a penetrometer with a constant frequency sound source mounted on it, (2) a hydrophone with a preamplifier, and (3) a receiver for processing the incoming data.

Penetrometer

The penetrometer (Figure 1) has two components: (1) a heavy, hydrodynamically shaped vehicle for speeding the penetrometer to the seafloor and for providing the impetus to penetrate the soil, and (2) an accurately controlled sound source for data measurement.

The vehicle is a lead-filled 2.45-m (8-ft) long, 90-mm (3½-in.) diameter pipe. A steel hemisphere is welded to the nose of the vehicle to provide an efficient hydrodynamic shape. The upper end is capped with a steel plate and center stud for attaching the sound source. Three equally spaced fins at the upper end provide stability for the falling penetrometer. The vehicle has a mass of 161 kg (11 slugs).

The sound source (Figure 2) consists of an acoustic projector, a power supply, electronic circuitry, and a protective pressure-resistant housing. It has a mass of 12 kg (1 slug), is 0.46m (18 in.) long, and is 90 mm (3½ in.) in diameter. The unit is screwed onto the stud provided at the upper end of the penetrometer vehicle. The acoustic output of the sound source is about 89 db above 0.1 Pa (1 μbar) at 1m, and this output level can be sustained for about 10 minutes. The frequency is 12,000 Hz±1 Hz. Immersion in water starts the sound source.

When the vehicle and the sound source are assembled, the penetrometer is a 173-kg (12-slug), 2.90-m (9½-ft) long, 90-mm (3½-in.) diameter package. The penetrometer attains a free-fall terminal velocity of 27 to 29 m/s (90 to 95 fps) and penetrates about 9m (30 ft) into soft, normally consolidated seafloor clays.

Hydrophone

The hydrophone used to pick up the signal from the penetrometer can be lowered 30m (100 ft) below the sea surface to reduce ship, wave, and other surface-generated noise. It has a plug-in bandpass preamplifier and an overall sensitivity of -65 db referenced to 1V per 0.1 Pa (1 μbar) of pressure. Other features include a 0.33-rad (19-deg) beam pattern at 12,000 Hz, and a front-to-back ratio of 20 db. Absolute level calibration facilities are also provided.

Receiver

The receiver is used to process the penetrometer data signal, which is Doppler shifted, that is picked up with the hydrophone. The hard-limiting receiver electronics consists of various bandpass filters and calibration crystals, a frequency converter, and a frequency discriminator. A self-contained sealed lead acid battery pack or line power can be used to operate the receiver. Numerous outputs are provided on the receiver, including raw frequency signal, converted frequency signal, and a voltage analog of the penetrometer's velocity. Time output is also provided with a 1-ms tick and a unique tick every 10 ms. The receiver components are housed in a splashproof aluminum case with appropriate control switches and plug-in jacks.

The high-gain hard limiter takes the incoming signal and amplifies it to saturation levels, thereby maximizing the low-end signal level that can be processed. The frequency converter then shifts the

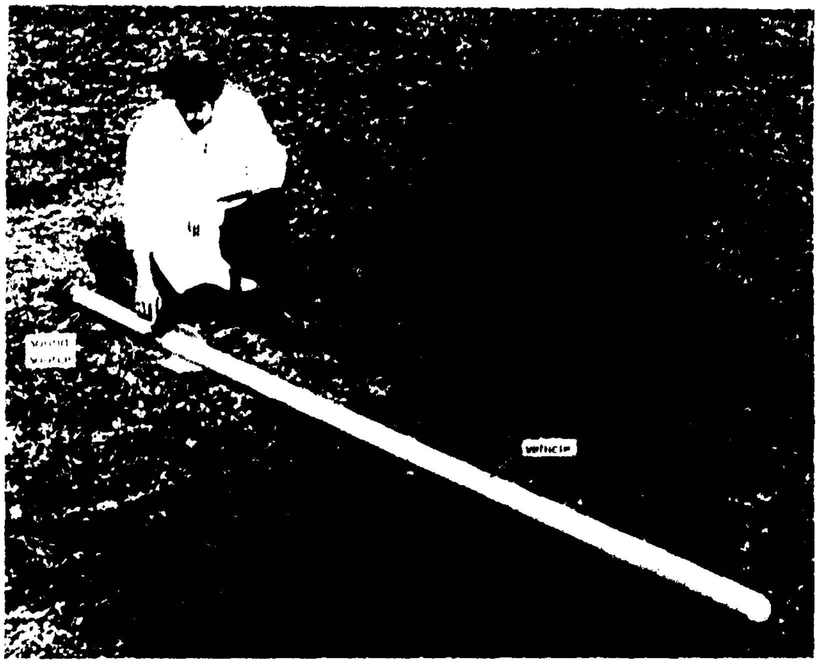


Figure 1. Expendable Doppler penetrometer.

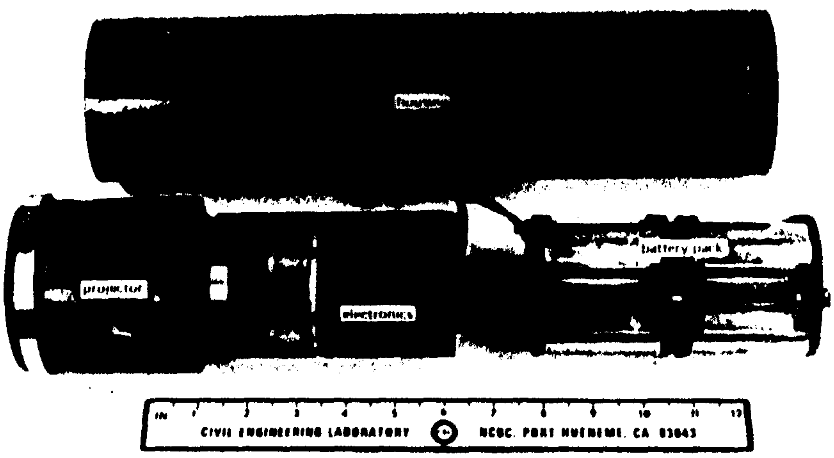


Figure 2. Sound source for penetrometer.

12,000-Hz signal down to a standard instrumentation frequency of about 3,900 Hz. This magnifies the Doppler shift as a percentage of the total frequency. Next the signal is processed by a frequency-modulated discriminator into a direct current voltage. The amplitude of the direct current voltage is the analog of the Doppler-shifted signal and is readily plotted or recorded.

THEORY OF OPERATION

The Doppler principle can be stated as

$$f' = f \frac{v}{v + v_s} \tag{1}$$

where f' = frequency received

f = frequency transmitted

v = velocity of sound of the immersion medium

v_s = velocity of source (penetrometer)

The 12,000-Hz signal emitted by the penetrometer is received by the hydrophone as a Doppler-shifted frequency and is processed by the receiver to obtain an analog of the penetrometer's kinematics. At the terminal velocity of the penetrometer, which is about 28 m/s (92 fps), and its operating frequency of 12,000 Hz, an 11,775-Hz signal will be received by the hydrophone if one assumes a seawater sound velocity of 1,463 m/s (4,800 fps). This is a frequency shift of 225 Hz or 1.8% of the 12,000 Hz signal of the penetrometer. In the range of velocities from 0 to 30 m/s (0 to 100 fps), the frequency shift is nearly linear at 8.04 Hz/mps of penetrometer velocity. The changes in the received sound are then a linear analog of the kinematics of the penetrometer. This frequency analog can be recorded and processed as is any frequency-modulated telemetry signal.

The required processing is accomplished in the receiver, and the analog signal is then recorded versus time. This recording can then be integrated to determine penetration depth and computer-reduced to estimate undrained shear strength versus depth.

DETERMINING UNDRAINED SHEAR STRENGTH

The soil failure around an advancing penetrometer is complex and difficult to analyze. Consideration of frontal bearing resistance, side resistance, buoyancy, "fluid" drag forces, and added mass need to be made. Analyzing the body motions of a penetrometer produces an undrained shear strength profile of the penetrated soil. This property is probably the most important soil property for anchor and foundation design in seafloor soil mechanics. The derived shear strength data will be more reliable for cohesive seafloors than for noncohesive seafloors. This is because partial drainage and other confounding factors in noncohesive soils multiply the difficulties of analysis.

The method used to analyze the data is that presented by True (1975). His method treats all the factors that were previously mentioned. The basic formulation is:

$$\text{Net Force} = F_D + W' - F_{BE} - F_{AD} - F_H \tag{2}$$

where F_D = externally applied driving force

W' = buoyant weight of penetrometer

F_{BE} = bearing pressure force

F_{AD} = side adhesion force

F_H = "fluid" drag force

The net force is the force causing the penetrator and any added mass to decelerate. The data reported herein gave best correlations when the added mass was ignored. This is a reasonable action based on added mass factors found in fluids for slender penetrators (Wendel, 1950). For the Doppler penetrometer, when treating the soil as a fluid, only about 1.5 kg (0.1 slug) of added mass are involved compared to a penetrometer mass of about 173 kg (12 slugs).

The soil shear strength terms have been formulated by True as:

$$F_{BE} = S_{\dot{\epsilon}} (S_u N_c A_f) \text{ and } F_{AD} = S_{\dot{\epsilon}} \left(\frac{S_u \delta A_s}{S_t} \right)$$

ere $S_{\dot{\varepsilon}}$ = soil strength strain rate factor

S_u = soil undrained shear strength

N_c = bearing capacity factor

A_f = penetrometer frontal area

δ = side adhesion factor

A_s = penetrometer side area

S_t = soil sensitivity

Undrained shear strength in cohesive soils is a function of strain rate, hence the application of a strain rate factor. However, the magnitude of the factor is in doubt. True recommends a maximum factor of 4. The work of Prevost (1976, p 1253) suggests that maximum strengths should be about 1.5 times conventional strengths (factor = 1.5) at most strain levels to 10% at maximum strain rates 100 times that of conventional strength tests (or 300% per hour). The strain rates during penetration of the Doppler penetrometer are at least 10,000 times greater than those during conventional strength tests and, therefore, Prevost's maximum would not seem appropriate. Analysis of the Doppler penetrometer data reported herein suggests, based on correlation to other available strength data, that a maximum strain rate factor of 2 is more appropriate than True's maximum value of 4 or Prevost's value of 1.5.

The side adhesion term of Equation 2 includes a side adhesion factor that varies over the length of the penetrator. This factor accounts for separation or reduced lateral pressure between the soil and penetrator. This variable side adhesion factor caused fluctuations in the derived shear strength data. Eliminating the term eliminated the fluctuations; therefore, the term has not been used in obtaining the data presented herein.

The drag force is calculated from the standard fluid drag equation

$$F_H = \frac{1}{2}\rho C_D A_f V^2 \tag{3}$$

where ρ = fluid (soil) mass density

C_D = drag coefficient

V = penetrometer velocity

The drag coefficient is calculated from the terminal velocity of the free-falling penetrometer.

Because the penetrometer is free-falling, there is no externally applied force during penetration, and Equation 2 becomes

$$Ma = W' - S_{\dot{\varepsilon}}\left(S_u N_c A_f + \frac{S_u A_s}{S_t}\right) - \tfrac{1}{2}\rho C_D A_f V^2 \tag{4}$$

where M = penetrometer mass

a = penetrometer deceleration

This equation is solved on an incremental basis to find undrained shear strength profiles.

To use Equation 4 assumptions must be made for the unit weight of the soil, the sensitivity of the soil, and the sound velocity of the near-bottom water. A parametric study of these parameters was made to assess their effect on derived undrained shear strength values. The unit weight assumption required for calculating the buoyant weight of the penetrometer was found not to be critical. Deviations up to 320 kg/M^3 (20 lb/ft^3) caused deviations in calculated strengths of 2% or less. Assuming 1,440 and 1,760 kg/m^3 (90 and 110 lb/ft^3) densities for loose and dense seafloors,* respectively, will usually give errors of 1% or less. The sensitivity of the soil was found to be more critical as it affects a large force term, side adhesion. For the Doppler penetrometer, where the side area is 100 times greater than the nose area, a 50% error in estimating the sensitivity will result in about a 25% error in the estimated strength profile. Usually the sensitivity can be estimated to less than a 50% error from data available on soils of similar geology. The sound velocity estimate is required to determine the velocity of the penetrometer from the Doppler frequency

*Density judged by penetration depth.

shift. These estimates can be made from sound velocity-depth-latitude data, such as those provided by Myers et al. (1969, pp 3-7). Good estimates of the sound velocity of the soil can be made by assuming the sound velocities in soft sediments (deep penetration) are the same as the bottom water, and for stiffer sediments (shallow penetration) that they are 5% higher than the bottom water. In general this will produce errors of less than 2% in the velocity data.

TEST PROGRAM AND PROCEDURES

Initial testing of the Doppler penetrometer was conducted to verify system design and general feasibility and to proof-test components. These tests, which totaled eight were conducted in water less than 30m (100 ft) deep in a sandy seafloor. Consequently, terminal velocity was not obtained, and penetrations were typically less than 1m (3 ft). The test results were presented by Beard (1976). The sound sources for these tests were prototypes of limited acoustic output. Based on the tests it was concluded that the concept of a dynamic penetrometer using the Doppler principle to gather data was workable, and that the instrument concept could accurately describe the velocity of the penetrometer.

To evaluate the penetrometer concept more thoroughly tests were required in a variety of sediments at greater water depths. Sound sources of increased acoustic output were required to conduct these tests. Prototypes of these sound sources were procured. They were pressure-tested at the Civil Engineering Laboratory and acoustically tested at the TRANSDECK facility of the Naval Undersea Center, San Diego.

Field testing of additional units was conducted at four sites off the southern California coast to determine the quality of data that can be obtained using the Doppler penetrometer. These sites ranged in depth from 180 to 1,700m (600 to 5,600 ft). Their locations relative to the coastline and their approximate geographic coordinates are presented in Figure 3.

With the exception of the 880-Meter Site, the engineering properties of the bottom sediment at these sites are known. Table 1 summarizes the types and quantity of data that have been obtained at each site. All of the data extend to a seafloor depth of 3m (10 ft) except for three cores that were taken at the 370-Meter Site; these are as long as 7.3m (24 ft).

Eleven expendable penetrometer tests were conducted—two each at the 880-Meter Site and three each at the other sites. Table 2 presents a summary of the tests conducted and a general soil classification of each test site.

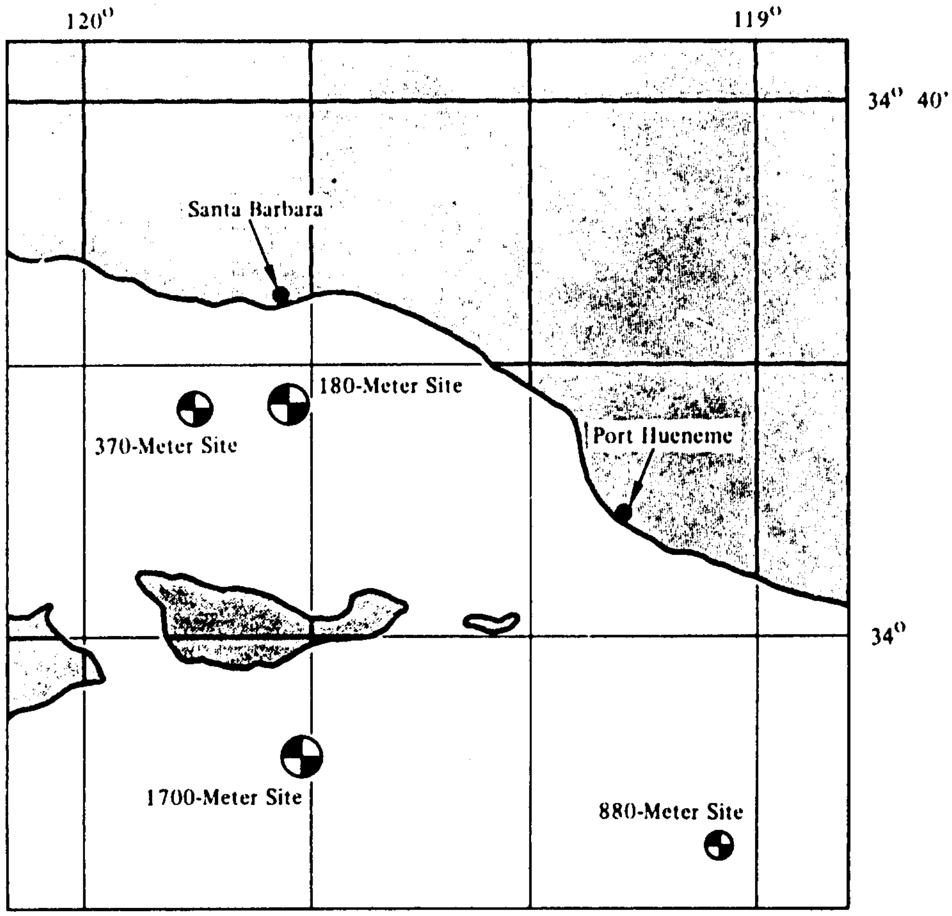
The general test procedure at each site was the same. The ship was brought on station using LORAC navigation. The hydrophone was placed in the water and lowered below the ship suspended on a bungee cord from a spar buoy. Calibrations were made at frequencies representing zero and about one-half terminal velocity. The sound source was checked for a watertight seal and test-started. The assembled penetrometer was placed over the ship's side and cast free. Raw frequency data, converter frequency data, a frequency shift analog, and time were recorded on magnetic tape. The analog data and time were also recorded on paper.

TEST RESULTS

The prototype sound sources were successfully pressure-vessel-tested to an equivalent water depth of 6,000m (20,000 ft). At TRANSDECK it was learned that the source output was about 89 db above 0.1 Pa (1 μbar) at 1m, and that this output level can be maintained for over 10 minutes.

About 15 minutes were required to perform an at-sea test that included placing the hydrophone in the water suspended from the spar buoy, making calibrations, placing the penetrometer over the side, recording data as the penetrometer fell, and recovering the hydrophone. Sea conditions were usually good, with a maximum sea state of 3 being experienced when testing at the 880-Meter Site. No difficulties were experienced testing at this sea state.

The field data acquired with the penetrometer were reduced to determine penetration depths and undrained shear strength profiles. Available sound velocity data near each site were used to determine the appropriate sound velocities for calculating a



Designation Site	Location	Latitude (N)	Longitude (W)
180-Meter Site	Santa Barbara Channel	34° 17' 12"	119° 42' 47"
370-Meter Site	Santa Barbara Channel	34° 16' 30"	119° 50' 58"
1700-Meter Site	Santa Cruz Basin	33° 51' 00"	119° 41' 00"
880-Meter Site	Santa Monica Basin	33° 43' 30"	119° 05' 00"

Figure 3. Location of test sites.

Table 1. Types and Quantity of Engineering Property Data Available at Each Test Site

Site	No. of Cores	No. of In-Situ Vane Shear	No. of In-Situ Cone Penetrometer
180-Meter	5	3	5
370-Meter	6	1	3
1700-Meter	1	–	2
880-Meter	–		

Table 2. Penetrometer Testing Program and General Conditions

Test Designation	Site	Soil Characteristics
180-P1 180-P2 180-P3	180-Meter	A nonuniform deposit varying from a sandy, clayey silt (ML) above 1m (3 ft) to a clayey silt (ML-MH) below. Soil appears to be over-consolidated and is strong.
370-P1 370-P2 370-P3	370-Meter	A uniform plastic clayey silt (MH). Plastic limit of 41% and liquid limit of 83%. Appears typical of deep ocean sea-floor sediments.
1700-P1 1700-P2 1700-P3	1700-Meter	A silty clay (MH) with an occasional sand lens. Plastic limit of about 70% and liquid limit of about 120%.
880-P1 880-P2	880-Meter	Uncored sediment thought to be a cohesive deposit based on embedment anchor test result.

calibration velocity corresponding to the calibration frequencies. This information is presented in Table 3. Soil impact time was selected by eye as the point of intitial deceleration on a deceleration-time trace. Penetration depths were calculated using the trapezoid rule to integrate the velocity-time curve from the time of impact to the time the penetrometer came to rest. Undrained shear strength profiles were determined using the method outlined in the section on calculating undrained shear strength from penetrometer data. Shear strength data for the last two depth increments of penetration for each test have been omitted because of difficulty in analyzing the data where the available soil resistance was high and the deceleration of the penetrometer was low.

180-Meter Site

Velocity versus depth data for tests conducted at the 180-Meter Site are presented in Figure 4. Penetrations were calculated to be 6.7m (22 ft), 6.4m (21 ft), and 5.8m (19 ft) for tests 180-P1, -P2, and -P3, respectively. The velocities at impact were 29.0, 29.6, and 28.3 m/s (95, 97, and 93 fps), respectively. The three shear strength profiles derived from the data are provided in Figure 5. The results compare favorably to the in-situ vane shear data, and the data from test to test seem to be repeatable. The average vane shear data are from three tests, with little data scatter from test to test. The penetrometer impact points may have been separated by distances up to 0.8 km (0.5 mi).

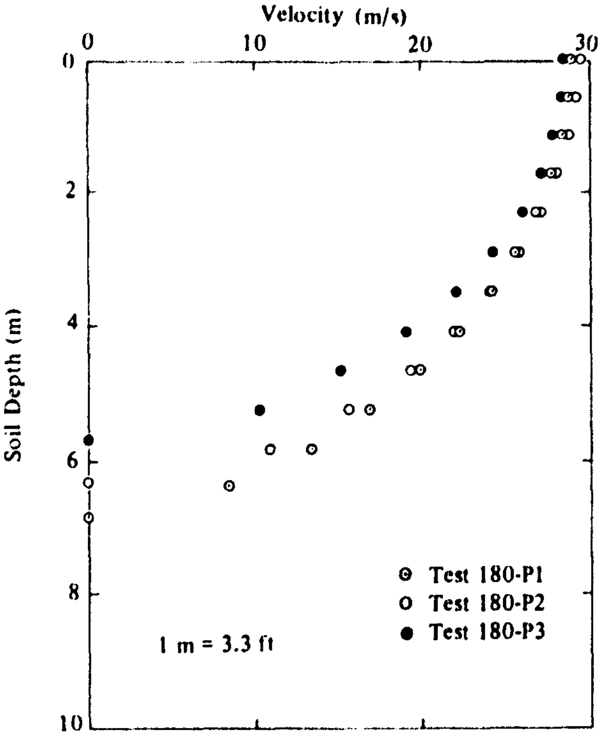


Figure 4. Velocity versus depth for 180-Meter Site.

Table 3. Calibration Velocities Corresponding to Calibration Frequencies at Each Site

Site	Sound Velocity at Site		Calibration Frequency (Hz)	Calibration Velocity	
	m/s	fps		m/s	fps
180-Meter	1,490	4,890	11,876	15.6	51.1
370-Meter	1,486	4,875	11,876	15.5	50.9
1700-Meter	1,490	4,890	11,876	15.6	51.1
880-Meter	1,484	4,870	11,876	15.5	50.9

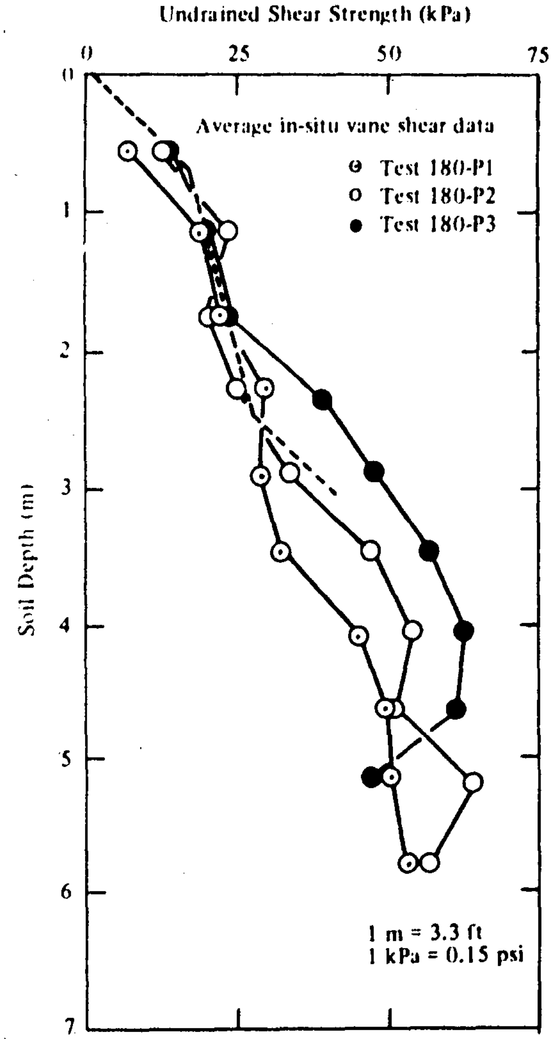


Figure 5. Undrained shear strength versus depth for 180-Meter Site.

370-Meter Site

Data for velocity versus depth of penetration are given in Figure 6 for the tests conducted at the 370-Meter Site. The respective penetrations for tests 370-P1 and -P3 were calculated to be 10.0m (33 ft) and 9.8m (32 ft). The data from test 370-P2 were not reduced because of a signal dropout part way through the penetration phase. Velocities at impact were 29.6 m/s (97 fps) and 28.3 m/s (93 fps), respectively. Figure 7 shows the calculated undrained shear strength profiles for these tests compared to undrained shear strength data taken on three piston cores recovered from the site. The penetrometer data compare well to the core data. At depths less than 3m (10 ft) there is more scatter in the core data than in the penetrometer data. At depths greater than 4.5m (15 ft) the scatter from core to core is little, and the scatter in the penetrometer tests is equally small. However, at these depths the penetrometer data average about 30% higher than the core data. Test 370-P3 was near the core locations, but test 370-P1 was about 0.8 km (0.5 mi) away.

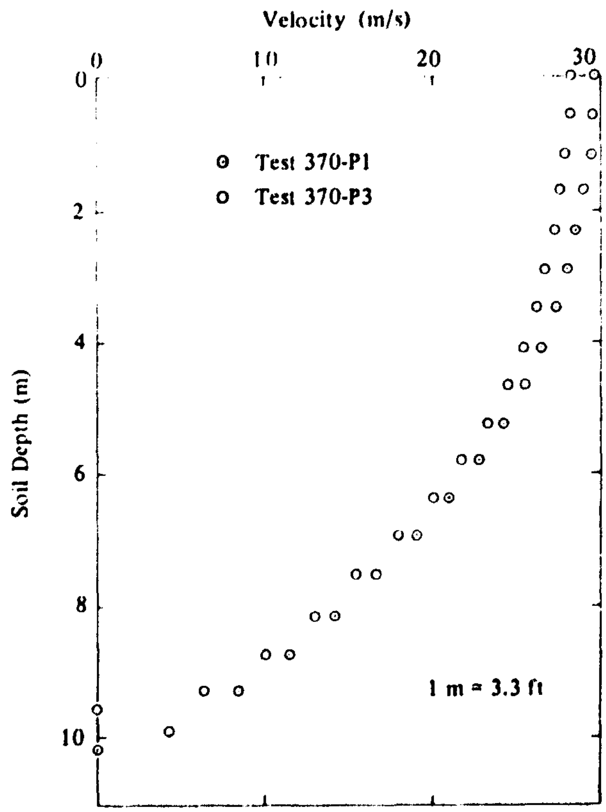


Figure 6. Velocity versus depth for 370-Meter Site.

1700-Meter Site

Figure 8 presents the velocity versus depth of penetration for tests conducted at the 1700-Meter Site. For tests 1700-P1, -P2, and -P3 respective penetrations were calculated to be 7.0m (23 ft),

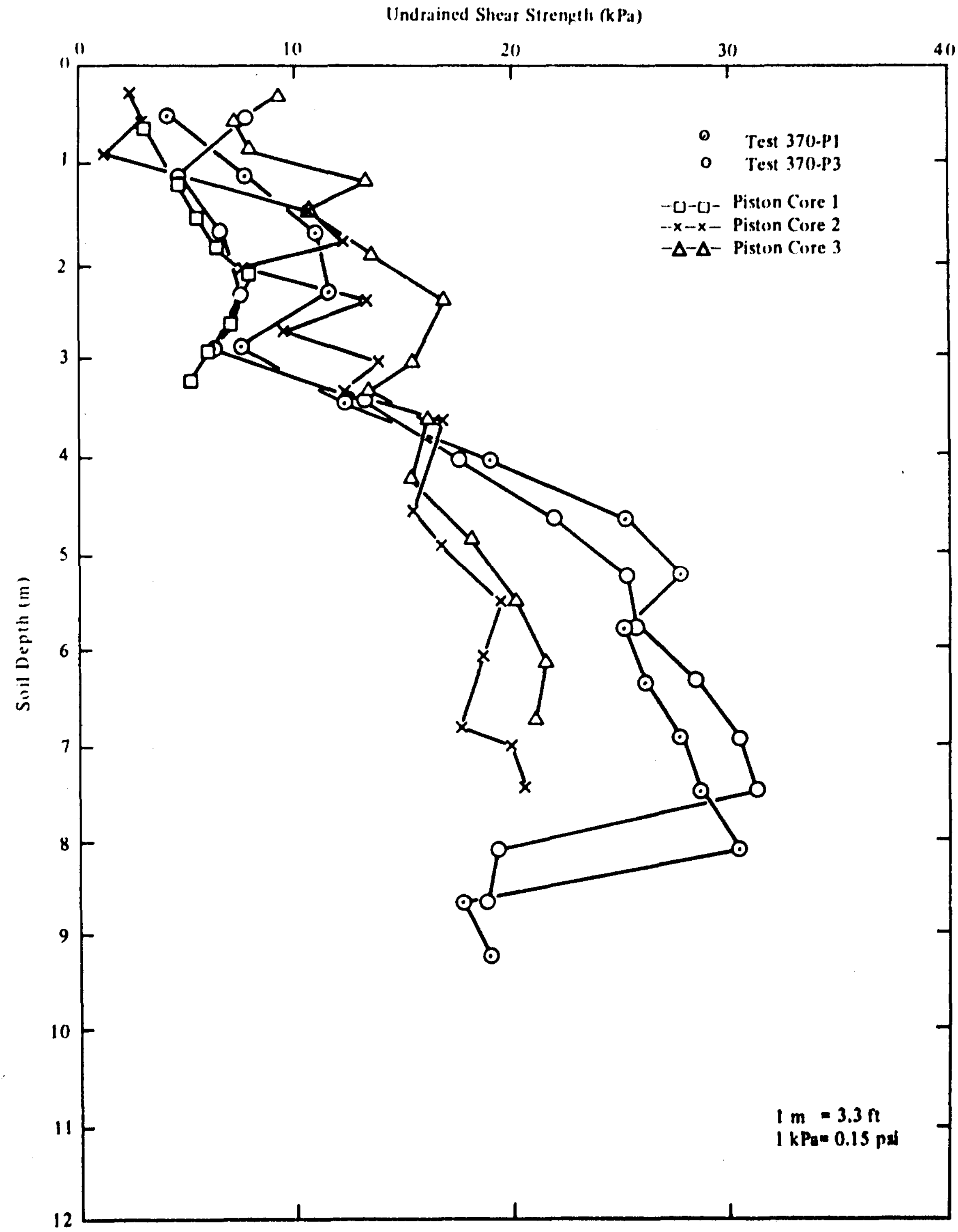


Figure 7. Undrained shear strength versus depth for 370-Meter Site.

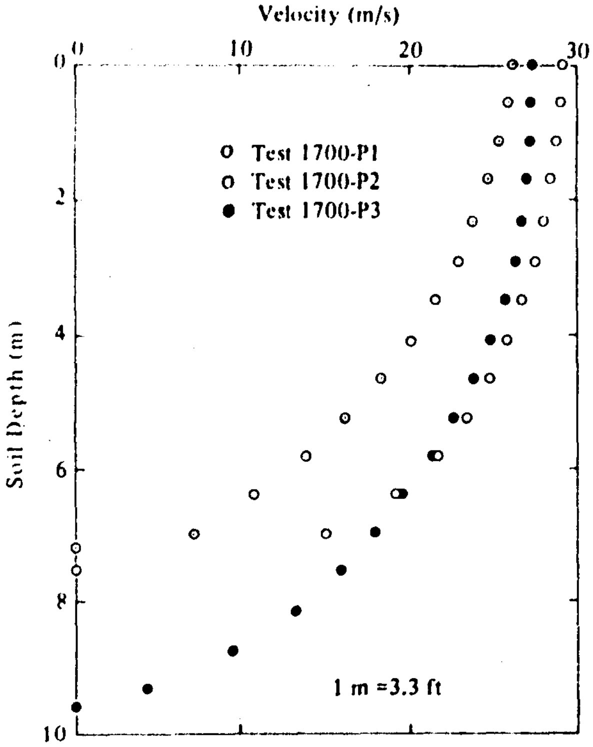


Figure 8. Velocity versus depth for 1700-Meter Site.

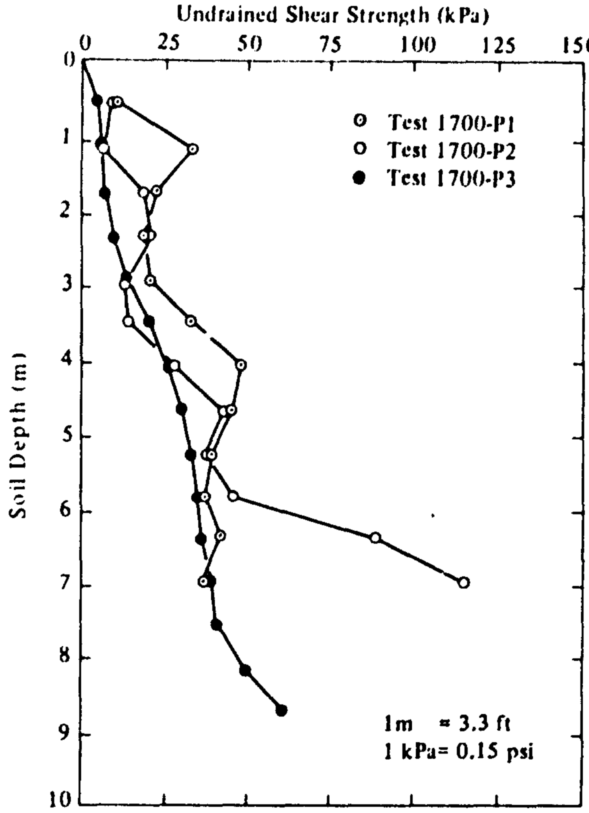


Figure 9. Undrained shear strength versus depth for 1700-Meter Site.

7.3m (24 ft), and 9.4m (31 ft). Velocities at impact were 26.2, 29.3, and 27.4 m/s (86, 96, and 90 fps), respectively. Undrained shear strength profiles were calculated from the test data and are presented in Figure 9. In general these tests do not compare well from one to another. However, each test location was about 1.6 km (1 mi) from the others. Only test 1700-P3 was at the location of existing core data. The penetrometer data from test 1700-P3 and the core data are compared in Figure 10; over the depth of the core the data compare fairly well. In Figure 9 note the high strength calculated at depths over 6m (20 ft) for test 1700-P2. These strengths seem reasonable when the velocity data in Figure 8 for this test are reviewed; i.e., during the last 1m (3 ft) of penetration the velocity dropped about 18 m/s (60 fps).

At this site the strength of the signal being received from each penetrometer was measured after each penetrometer was buried in the seafloor. The length of time the signal lasted was also noted. The excess signal measured was conservatively 20 db, and signals were detected for periods of 1 to 2 hours.

880-Meter Site

Velocity versus depth data are presented in Figure 11 for test 880-P1. The calculated penetration for this test was 6.7m (22 ft). The velocity at impact was 27.3 m/s (90 fps). On test 880-P2 the signal abruptly went from terminal to zero velocity, indicating that the penetrometer had struck something other than soil. The undrained shear strength profile calculated from test 880-P1 is presented in Figure 12. There are no data to compare these data to.

DISCUSSION

In general the expendable Doppler penetrometer performed well. Pressure vessel testing showed that the sound source pressure housing is good to a 6000m (20,000-ft) water depth. Based on the acoustic output

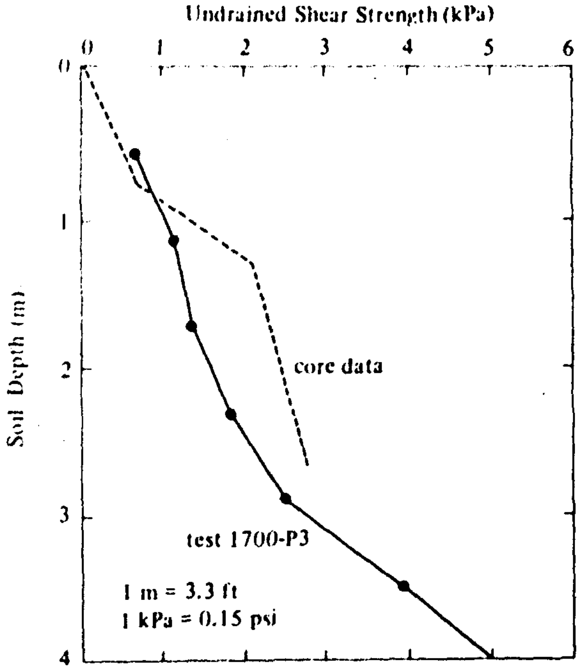


Figure 10. Comparison of undrained shear strength calculated from test 1700-P3 and data from core at the site.

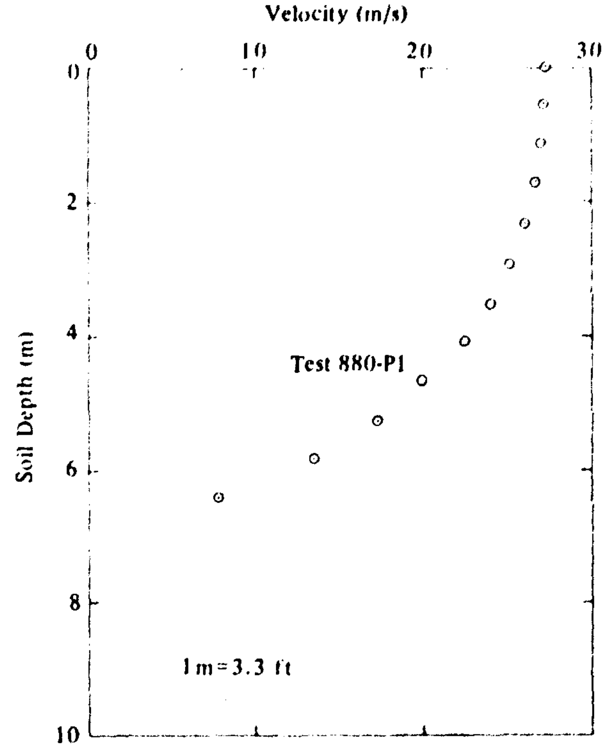


Figure 11. Velocity versus depth for 880-Meter Site.

measured at TRANSDECK the source should be acoustically sufficient to operate to the 6,000-m (20,000-ft) design depth. This was substantiated during testing in 1,700 m (5,600 ft) of water where, after the source was buried with 6m (20 ft) of sediment, more than enough signal level remained to detect the penetrometer in 6,000m (20,000 ft) of water. Operationally it has proved to be simple to use, and it takes little ship-time to perform each test. The length of time the signal can be detected was a problem, as another test could not be performed at a given site until the signal was gone (the two signals would interfere). This could be prevented by having a timing circuit that shuts the sound source off after 10 minutes or so. Deployment of the penetrometer has taken place under sea state 3 conditions with no difficulties occurring.

Of the 11 penetrometers dropped, nine provided good data for estimating undrained shear strength profiles. Of the other two, one did not penetrate due to hitting either rock or debris, and the other did provide data that can be analyzed, but more effort will be required than on the other nine tests. The instrumentation has been shown to be dependable. This can be ascribed to the instrument's simplicity and the fact that it has to work for only a short time.

Penetrations were in the range of the design, which was 9m (30 ft) plus in soft sediments. Tests 370-P1, 370-P3, and 1700-P3, where penetrations were 10.0, 9.8, and 9.4m (33, 32, and 31 ft), respectively, confirm the penetrometer's penetration capability. Calculated penetrations are quite accurate as reported by Beard (1976). Even in soft soils little difficulty was encountered in determining the impact time, which is the most significant factor in determining depth of penetration.

The data obtained with the penetrometer look quite good; see Figures 5, 7, 9, 10, and 12. Correlation to existing undrained shear strength profiles was particularly good at the 180-Meter Site, with satisfactory results at the 370- and 1700-Meter Sites. (No correlation was made at the 880-Meter Site because there were no existing data.) These correlations were

made with the advantage of knowing the soil density, soil sensitivity, and speed of sound parameters. These would normally have to be estimated. However, parametric studies have shown that soil density has little effect on the data, and that a reasonable sound velocity estimate from a source such as Myers et al. (1969, pp 3-7) will be sufficient to limit errors to a few percent. Soil sensitivity can have a large effect, and it is the greatest potential source of error with the slender Doppler penetrometer. A 50% error in the estimated soil sensitivity will result in 25% error in the calculated undrained strength. A shorter penetrometer would result in a lower potential error. For most marine sediment types, an estimate of the soil sensitivity from existing data with less than a 50% error should be possible.

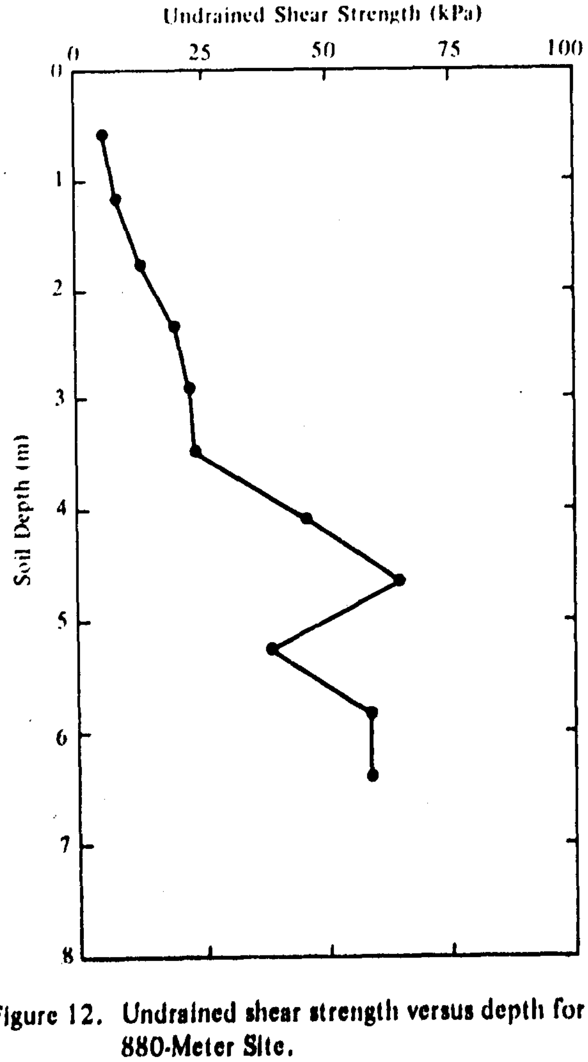


Figure 12. Undrained shear strength versus depth for 880-Meter Site.

CONCLUSIONS

1. The Doppler instrumentation system is a reliable and simple method for monitoring the motion of a free-falling penetrometer. The system described herein is capable of operating to water depths of 6,000m(20,000 ft).
2. The performance of the Doppler penetrometer is sufficient to meet its objective as it will provide data to 9-m (30-ft) soil depths.
3. Undrained shear strengths calculated from Doppler penetrometer data can be reasonable (+30% or less of actual values) even though the penetration phenomenon is complex.
4. Most factors affecting the Doppler signal or the data analysis either lead to small errors in or can be reasonably estimated for calculating the undrained shear strength. This is not true of the soil sensitivity. It must be estimated with care as significant errors (25%) can be induced by a 50% error in soil sensitivity.
5. The expendable Doppler penetrometer is a simple, reliable, and expedient tool for investigating the strength of seafloor deposits.

RECOMMENDATIONS

1. Future penetrometer sound sources should include a timing circuit to shut themselves off after about 10 minutes of operation. They should also have the signal output reduced by about 20 db from the present level to save money on the cost of the projector. This signal strength reduction is possible when the penetrometer is used in conjunction with a hydrophone receiver comparable to the system described in this report.
2. Continued performance evaluation should be made in a range of seafloor sediment types.

EPILOGUE

The expendable Doppler penetrometer has been successfully tested at a water depth of 5430m (17,800 ft). Penetration into a pelagic clay exceeded 8m (26 ft). Excess signal levels measured with the sound source buried 5m (16 ft) were about 20 db.

ACKNOWLEDGMENTS

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